SEDIMENT TRANSPORT IN THE JEQUETEPEQUE RIVER AND ITS IMPACT ON THE GALLITO CIEGO DAM, PERU

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ABSTRACT

This research focuses on evaluate the annual rate of sediment transport of the Jetepeque River, located in the northern of Peru, and its effect on the Gallito Ciego Dam. This dam, which started its operation in April 1988, is one of the most important of the regulated basins in Peru and the last ten years has reduced its capacity by more than 20 % due to the sediment discharge into the reservoir from the upper basin. For this study, a record of peak flows (1920-21, 1987-88) of Ventanillas hydrometric station (07 º 17'S, 79 ° 17'W), the technical characteristics of the dam and the overall results of bathymetry (April, 1999) were used. Gumbel probabilistic model and the empirical equation of Meyer-Peter were used to predict the flows and annual sedimentation in the reservoir, respectively. The results are consistent with the predicted rate by this study (9 x 106 m3 per year) and those obtained from bathymetric studies (8.82 x 106 m3 per year); however, both are highly divergent with the design rate of the project (1.7 x 106 m3 per year), which evidences a weakness of the original sedimentological study, in addition, by the lack of water management programs and sediment control causing the early failure of the dam. Furthermore, the active storage of the reservoir has been reduced considerably.

Keywords: Sediment transport, Jequetepeque River, Gallito Ciego Dam.

1. INTRODUCTION

Since a long time ago, large dams in the world have been built primarily social purposes, where hydropower and agriculture are almost always the primary objectives. However, in many cases, high rates of erosion in catchments and high rates of sediment transport have dramatically reduced lifespan, truncating the slow recovery of investment in the projected horizon and causing economic losses, with serious implications for the poorest countries (Icold, 2008). The reality is similar in Peru, especially with large dams located in the lower areas of the watershed North Pacific, where the basins are characterized by steep, steep slopes, unstable soils, sparse vegetation coverage, and periodic regimes of intense and frequent rainfall, determining highly degrading and very unfavorable natural conditions for large dams located in that region (Rocha, 2006). Likewise, the inappropriate activities undertaken by man and aggressive periodic phenomena of El Niño, have significantly contributed to the early collapse of the Gallito Ciego dam. This shows that dam projects must be suitable to the degrading characteristics of each basin and not the other way as before, try to adjust the basin to the life of the already constructed dam, the latter is a pure utopia, taking into account the costs of watershed management plans and sediment control are too high and significant results are achieved in the long term (reforestation, for example). If to this we add the conservation costs, the dam projects in watersheds with high rates of degradation and transport of solids are practically impossible (Icold, 2008). This paper intends to show that, even if no information is available of sediment transport, proper use of indirect methods may be sufficient for the feasibility study of large dams.

2. MATERIALS AND METHODS

Study Location

Gallito Ciego dam, the Special Project Jequetepeque - Zaña. PEJEZA, is located in northern Peru, district of Yonan province of Contumaza, and department of Cajamarca, with 320 m above sea level. This dam began operating in April 1988, allowing regulates the water of the Jequetepeque river for hydropower generation and irrigation in the departments of La Libertad and Lambayeque. The catchment upstream of the dam has been developed between 320 and 4200 meters above sea level, determining a total area of 3443 km2, with irregular and steep reliefs, limited vegetation coverage, where the regime, temporal and spatial variability of extreme precipitation determine aridity conditions and rainfall concentration from January to March.

The relevant aspects for this study constitute the dam characteristics, essentially, dead capacity, storage of sediments during the projected design life, and the volumetric result from bathymetric studies. These features, and others, are shown in Table 1.

Table 1. Specifications of Gallito Ciego Dam *

Description	Features
Dam	
Nature	Land zoned or symmetrical, with core and screen concrete.
Base width (m)	700
Crown width (m)	12
Height (m)	105
Altitude (masl)	320
Type regulation	Multiyear
Reservoir	
Design life (years)	50
Dead Capacity (MCM)	85
Net capacity (MCM)	400
Flood retention capacity (MCM)	86
Total capacity (MCM)	571
Maximum mirror of open water (Ha)	1 420
Economic indicators	
Benefit / cost	0.70
Investment Cost (Millions of Dollars)	570
Bathymetry	
April 1999 (MCM)	97
Operation	
Start-working	April, 1988

* Source: PEJEZA Project
MMC = Million cubic meters

Forecast maximum liquid flow rates

The maximum liquid flow forecast of Jequetepeque River was performed using the probabilistic model Gumbel (1), which was shown to have better goodness of fit, according to Kolmogorov-Smirnov criterion. The adjustment was made using annual data from a sample of 67 years (1920-21, 1987-88) observation maximum annual discharges from the Ventanillas station (07º17' S, 79º 17' W.- National Service of Meteorology and Hydrology. SENAMHI, Peru) (Aparicio, 1992).

$$F(x < X) = \exp\left[-\exp(-\alpha(x-\beta))\right] \quad [1]$$

$$T_r = \left[F(x \le X\right]^{-1} = \left[1-(1-j)^{1/N}\right]^{-1} \quad [2]$$

$$x = \beta - \alpha^{-1} Ln\left[-Ln\left(1-T_r^{-1}\right)\right] \quad [3]$$

$F(x < X)$ is the cumulative probability that any event x will be less than X

α is the scale parameter

β is the positional parameter

j is the uncertainty

T_r is the return period, years

N is the period of consecutive years.

The model parameters were measured (α =0.004580, β =174.8104) by the method of moments, then after, the simulation of the adjusted model.

Production and sediment transport

The estimation of sediment transport components was performed by indirect methods due to the lack of sediment data.
The potential production of sediments in the basin and delivery to Jequetepeque river, in the form of suspended material represented by the specific rate of solids (q_S: t ha^{-1} yr^{-1}) was estimated using equation (4). The selection of this equation is justified, not only for its simplicity but because it involves the most degrading parameters of the basin related to the rainfall and relief (Spalletti and Brea, 1998).

$$q_S = 2.65 \log (P/P_*) + 0.46 \log(C_O - 1.56) \quad [4]$$

where,

P is the annual rainfall module, mm

P_* is the maximum precipitation of the month, mm

C_O is the orographic factor, dimensionless.

The values of parameters and variables of this basin are: annual rainfall module, 1000 mm; maximum rainfall of 136 mm month (March); orographic factor, 35%; specific weight solids 1650 kg m-3; basin area 3443 km2; compaction ratio, 1.2.

Dimensional model of the Meyer-Peter, given by equation (5), in order to estimate the specific capacity bed load transport (kg s-1 m-1 QS) is also selected. It is based not only by the simplicity of the model, but also by adapting to the limited conditions of the methodology, related the nature and slope of the riverbed and involves the most important hydraulic parameters of the reach section of river-dam.

$$Q_S = (250 q^{2/3} S - 42.61 d_{Sm})^{3/2} \quad [5]$$

where,

q is the specific liquid flow of flood, m^3 s^{-1} m^{-1}

S is the hydraulic gradient, dimensionless, m * m^{-1}

d_{Sm} is the average diameter of solid, m.

The values of the parameters and variables of the delivered reach section are: channel slope, 0.013; average channel width, 40 m; average diameter of solid, 0.002 m; specific weight solids 1650 kg m-3; wet sediment transport by water year period average, 90 days (January to March); compaction coefficient, 1.2.
The value of annual forecast rate of sedimentation, considering the suspended and bedload components, is contrasted with the values of the rates coming from the bathymetry and project design to measure the quality of sedimentological study and explain the causes of early fill-sediment or premature failure of the dam.

Sedimentation according linear model based on bathymetric results

Theoretically, assuming a linear model, based in the historical past of first eleven years of Gallito Ciego dam operation, taking as origin the first year in Abril, 1988, equation (6) was obtained; where, the numeric constant of the second member represents the rate of annual sedimentation. This equation can be used to extrapolate futures values of sedimentation, to follow the post failure evolution or "agony" of the dam, until "the physical death" (Palau, 2002).

$$V_S = 8.82 * 10^6 \ T \quad [6]$$

where,

V_S is the settled volume, m^3

T is time, years.

The expression above is fairly representative to simulate future deposits, taking into account that during the historical period of the short lifespan of the dam (under 10 years), has had to endure the effects of up to two severe phenomena El Niño in the 90s (1991-1993, 1997-1998).

3. RESULTS AND DISCUSSION

Prediction of fluid flow sediment transport

Calibrated simulation model yielded an annual maximum liquid flow of Jequetepeque river for several uncertain conditions and frequency. For this study, the average discharges (J = 50%) and higher recurrence (N = 2) during the wet season of flooding in a normal hydrological year are relevant interest. Criteria that allowed select the discharge of 372 m3 / s, as representative of normal wet period from January to March (90 days). Assuming this flow as a permanent along the wet periods in order to cover not only the El Niño effects, but also sediment transport.

It is considered herein that the liquid flows transport the solid material estimated using equation (4), as a suspend sediment to the dam. Similarly, it is considered that the total transport capacity of bed of the delivery reach estimated using equation (5), is 100% solid material of tow to reach the dam. Both assertions are valid for a basin with high rates of sediment transport.

Prediction of annual sediment transport and sedimentation rate

The results of sediment transport components, converted to sedimentation rates are presented in the Table 2.

Table 2. Components of sediment load and sedimentation rate

Load of sediment delivery	Compaction factor	Sedimentation rate (MCM*/year)	Percentage of total (%)
Suspended or	1.2	0.52	5.8
bed	1.2	8.48	94.2
Total sedimentation rate	-	9.00	100

MCM* = Millions of cubic meters

The influence of bed-drag material, 94%, compared with only 6% of suspended material, clearly denotes the incompatibility in behavior of these basins, compared to those with dense vegetation coverage (Amazon). The drag material, mostly from the movement of large masses by slope destabilization, is difficult to control in the basin, due to that soil management is basically addressed at decreasing the suspension component. The drag component, however, is controlled by the sediment dams that do not exist in this project.

Sedimentation rate as bathymetry

The Volumetric results from the only on bathymetry carried out (April, 1999) after 11 years of operation of the dam Gallito Ciego, show that there is in the dam an accumulated total volume of sediments around 97 x 106 m3 (97 MCM) representing an average real rate of sedimentation of 8.82 x 106 m3 yr-1 (MCM 8.82 year -1), consistent value with the forecast obtained in this study (Table 2). The sedimentation rate observed is indicative that the design life of the dam would be over before to get ten years of operation, since the expected life capacity was only limited to 85 MCM (Table 1).

Sedimentation rate project design

The project includes a dead capacity of 85 x 106 m3 (85 MCM) linked to a projected 50 (Table.1) life; which is obviously an average rate of sedimentation in the reservoir equivalent to 1.7 x 106 m3 yr-1 (MCM 1.7 yr-1), this value is highly discrepant with observed sedimentation rates and forecasted in this study.

Table 3. Summary results of sedimentation rates for the dam Gallito Ciego

Parameter	Foundation	Value (MMC/year)
Observed rate (bathymetry)	97 MMC/11 year	8.82
Rate Forecast	Results of this study	9.00
Rate project design	85 MMC/50 year	1.70

The high discrepancy between the observed rates of sedimentation (bathymetry) - consistent with the forecast rate of this study-and the rate of project design, constitutes, obviously, an exaggerated weakness of sedimentological study. The lack of data on sediment transport does not constitute a valid justification argument, because we see that indirect methods give very approximate results if they are used considering its limitations and always acting on the side of safety. Discuss in detail latter aspect cannot be done here by not having the technical document.

Evolution of sedimentation according linear model based on the bathymetry

The results of the bathymetry derived by the linear model forecast that the settled total or "physical death of the reservoir would be producing around 2040.

The lack of plans and programs for watershed management and sediment control, and the effects of El Niño, have contributed to the accelerated sedimentation of the dam and thus, the premature collapse. The dismantling will be another problem, not only by the high costs involved, but also by the potential risks of an earth dam with completely silted reservoir.

Currently, the settled volume in the reservoir, as well as depleting the dead capacity (85 MCM), has invaded the available volume, reducing by about 144.32 x 106 m3, equivalent to 36% of its usable storage capacity. This accelerated reduction of the dam capacity will contribute to social and environmental problems, each time more intense.

4. CONCLUSIONS

The early collapse of the dam Gallito Ciego is due to deficiency of sedimentological study, having reduced the lifetime to less than a fifth (less than ten years) of the projected (50 years) economic life. This shows that not all basins are apt to be regulated by large dams and their viability depends entirely on the consistency and validity of the hydrological study on sedimentology.

The arguments of the lack information of sediment transport to justify the weaknesses of the sedimentological studies of large dams, does not have basis today, since the judgment in the selection and application of indirect methods may be sufficient to estimate dead storage capacity of such structures, as this study evidences.

The sudden reduction of the economic horizon of this project not only truncated substantial return on investment, causing severe economic losses to the country, but also trigger social and environmental problems. This shows that even when there are favorable conditions of runoff and topographical and geological benefits for a large dam, it will be not possible if it is established that there are excessive contribution of solids.

This failure should be taken as a learning experience in engineering of large dams, to not regulate catchments with highly favorable characteristics to water erosion and sediment transport, such as the basins of the Pacific coast of Peru; very special for those in the north, where our regulated basin of this study is located. The prevalence of sediment transport component, more than 90% of the total, becomes unmanageable through reforestation, having to resort to the famous dam sediment as control measurement.

As will be understood, it is very complicated and expensive to change the characteristics of excessive direct runoff in watersheds with high rates of water degradation, resulting mostly unworkable plans and programs for watershed management and sediment control, as alternatively protection of large dams. Therefore, watershed regulation by large dams is only justifiable for those protected and managed.

While the costs are very expensive, it is desirable that the bathymetric studies of large dams are carried out systematically and regularly, in order to measure the evolution of sedimentation in the reservoir, allowing making necessary adjustments to the management plan, sediment control, and improved profitability. In regulated basins unmanaged without technical operations of dams, where the only bathymetry study was carried out after eleven years operation as happened Gallito Ciego dam, has only served to testify the "economic premature death."

The alternative to improve water use in highly degradable basins, is implementing plans to improve groundwater recharge, between this, soil management through reforestation and micro regulations with small dams located in the Andean systems, as was done in times pre-Inca cultures.

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